SPRAY ANGLE AND DROPLET SIZE ANALYSIS FOR GAS TURBINE FOGGING

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DEDICATION

To my lovely father and mother, who gave me endless love, trust, constant encouragement over the years, and for her prayers. To my Family, for their patience, support, love, and for enduring the ups and downs during the completion of this thesis. This thesis is dedicated to them.

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ABSTRACT

The performance of fogging impaction pin nozzles is highly dependent on the spray droplet sizes and spray angles. The risk of compressor blade erosion and corrosion increase if large water particles are present. In the compressor path, effective water droplet evaporation is determined by droplet sizes, water droplets distribution, and concentration within the fogging system. Big droplets are hard to evaporate in time and will invade on Gas Turbine Air Inlet Guide Vane and compressor blades and eventually cause erosion and corrosion due to water hammering. The sizes of droplet and spray angles depend a lot on the impaction pin angles and nozzle orifice geometry but their relationships causing water hammering is still unknown. This study aimed to establish relationships of impaction pin angles and nozzle orifice diameters geometrical effect towards spray angles and droplets sizes for Alstom GT13E2 Gas Turbine inlet fogging. Both experimental data and numerical techniques were used in this research. Image Feature Consolidation Technique and shadowgraph methods were used in the experimental works to capture and analyse the flow output from the impaction pins. Two-dimensional and three-dimensional numerical techniques were employed by varying pressure and pin angles to determine their effects on the spray angles. A multiphase model was used in numerical modelling. The results showed that the small nozzle orifices and small impaction pin angles operated at high pressure produced smaller droplet sizes. A high-pressure flow seemed to produce a smaller spray angle. The spray angle was increased by almost 50% if the orifice size was reduced by 0.5mm. The spray angle was increased about 6% when the pin angle was reduced from 60° to 45° and 2% for pin angle reduction from 45° to 30 °. This research reveals that the optimized impaction pin angles for Alstom GT13E2 Gas Turbine are 30° to 57°. With that, the number of nozzles can be optimized by 7%. Three reference charts, namely Number of Nozzle Chart (NONC), Spray Angle Chart (SAC), and Number of Nozzle According Orifice Size Chart (NONAOSC), are established from this research. The charts can be used to estimate the number of nozzles that are needed for Alstom GT13E2 Gas Turbine model operation, which is according to pin angle and orifice size.

ABSTRAK

Prestasi muncung pin impakan pengabusan sangat bergantung pada saiz titisan semburan dan sudut semburan. Risiko hakisan bilah pemampat dan kakisan meningkat jika terdapat zarah air yang besar. Dalam laluan pemampat, penyejatan titisan air yang berkesan ditentukan oleh saiz titisan, pengedaran titisan air, dan kepekatan dalam sistem pengabusan. Titisan besar sukar disejat sepenuhnya dan akan menghakis pada Vane Pemandu Masuk Udara Turbin Gas dan bilah pemampat dan akhirnya menyebabkan hakisan dan kakisan kesan daripada tukulan air. Saiz titisan dan sudut semburan banyak bergantung pada sudut pin impak dan geometri orifis muncung tetapi hubungannya yang menyebabkan tukulan air masih tidak diketahui. Kajian ini bertujuan untuk mewujudkan hubungan geometri impakan sudut pin dan diameter orifis muncung terhadap kesan sudut semburan dan saiz titisan untuk pengabusan masuk Turbin Gas Alstom GT13E2. Kedua-dua data eksperimen dan teknik berangka digunakan dalam penyelidikan ini. Teknik Penyatuan Ciri Imej dan kaedah graf bayangan telah digunakan dalam kerja-kerja eksperimen untuk menangkap dan menganalisis keluaran aliran daripada pin hentaman. Teknik berangka dua dimensi dan tiga dimensi telah digunakan dengan tekanan yang berbeza-beza dan sudut pin untuk menentukan kesannya pada sudut semburan. Model berbilang fasa digunakan dalam pemodelan berangka. Keputusan menunjukkan bahawa orifis muncung kecil dan sudut pin impak kecil yang dikendalikan pada tekanan tinggi menghasilkan saiz titisan yang lebih kecil. Aliran tekanan tinggi nampaknya menghasilkan sudut semburan yang lebih kecil. Sudut semburan meningkat hampir 50% jika saiz orifis dikurangkan sebanyak 0.5mm. Sudut semburan meningkat kira-kira 6% apabila sudut pin dikurangkan daripada 60° kepada 45° dan 2% untuk pengurangan sudut pin daripada 45° kepada 30°. Penyelidikan ini mendedahkan bahawa impakan sudut pin yang dioptimumkan untuk Turbin Gas Alstom GT13E2 ialah 30° hingga 57°. Dengan itu, bilangan muncung boleh dioptimumkan sebanyak 7%. Tiga carta rujukan, iaitu Carta Bilangan Muncung (NONC), Carta Sudut Semburan (SAC), dan Carta Saiz Orifis Muncung (NONAOSC), telah diwujudkan daripada penyelidikan ini. Carta ini boleh digunakan untuk menganggarkan bilangan muncung yang diperlukan untuk operasi model Turbin Gas Alstom GT13E2, iaitu mengikut sudut pin dan saiz orifis.

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LIST OF ABBREVIATIONS

GT - Gas Turbine
GB3 - Generation Block 3
SEV - Segari Energy Ventures
CFD - Computational Fluid Dynamic
ISO - International Organization for Standardization
KKS - Kraftwerk Kennzeichen System
OEM - Original Equipment Manufacturer
Uitm - Universiti Teknologi Mara
PLC - Programmable Logic Controller
RH - Relative Humidity
CMOS - Complementary Metal–Oxide–Semiconductor
IFCT - Image Feature Consolidation Technique
DOF - Depths of field
SMD - Sauter Mean Diameter
LPM - Litre Per Minute
VOF - Volume of Fluid
DPM - Discrete Phase Model
DSD - Droplet Size Distribution
DMLS - Direct Metal Laser Sintering
GE - General Electric
NDA - Non-Disclosure Agreement
FOD - Foreign Object Damage
LPP - Lumut Power Plant
O&M - Operation and Maintenance
CAPEX - Capital Expenditure Budget
SMD - Sauter Mean Diameter

LIST OF SYMBOLS

α - Impaction Pin Angle
β - Impaction Pin Nozzle Orifice Diameter
ρ - Water Density
μ - Water Viscosity

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Gas turbines (GT) are sensitive to the changes in ambient temperature and pressure because it is an air-breathing engine. Whenever the ambient air temperature is increased, the GT power output will be decreased (Domachowski and Dzida, 2015). This is because of the reduction of mass flow for intake air when the air density is reduced. Besides that, turbomachinery performance will drop over a period of time (Poullikkas, 2019). The loss of GT power output will be retained when the inlet air is being cooled (Mee, 2014; Athari *et al.*, 2015) , and the power increased is in the range of 1.85-16.8MW. For every 1°C escalation in ambient temperature, the gas turbine (GT) active power will be reduced 0.54%-0.90% (Mee, 2014). A high ambient temperature causes a decrease of air droplet density, hence limits the air mass intake to the compressor. Hence, less combustion occurs, and this causes a drop-in power output (Bohrenkämper *et al.*, 2004). One way to counter this limitation is to install a system to cool the gas turbine inlet air to the possible lowest air temperature. Marine gas turbine is also using this method of enhancement (Domachowski and Dzida, 2019).

GT inlet duct water injection method is considered as famous and a well-established air inlet cooling tool nowadays. We can call this technique as Gas Turbine air inlet fogging. In this technique, nozzle arrays will inject the fine water droplets mist into the Gas Turbine air intake in the form of “fog” (Suneetha et al., 2013). Normally, the system is installed at the Gas Turbine air filter house. Almost all of the fogs evaporate prior reaching the compressor inlet when intake air (at given surrounding ambient conditions) has been saturated by the required amount of water injection (Series and Science, 2020). The outcome of this cooling process will decrease the inlet temperature to the compressor (Farokhipour, Hamidpour and Amani, 2018). Consequently, the drop of Gas Turbine active power will be recovered (Kwon *et al.*, 2018). Dry and hot environments will get a supreme advantage of this cooling method because the effectiveness of fogging cooling process is very much subjected to air humidity and temperature, and the effectiveness high when humidity is low (Sanaye and Tahani, 2010). However, moist and tropical atmospheres also can still gain the usefulness of this cooling scheme (Mee, 2014). Gas turbine and combined cycle power plants have started to use inlet fogging as a power extension method to boost the power output (Ehyaei *et al.*, 2015).

A series of nozzles distributes the demineralized water under high pressure which in turn atomizes the water into fine droplets in the form of fog. Due to its small size and distribution over a large area, the water droplets evaporate quickly and effectively cooling he air. Fogging can achieve 100% saturation of air and can cool it down to the wet bulb temperature (El-awad, 2008). However, the successful of a good fogging system installation is depending on the water droplets which must be small and fine enough to evaporate fully in the path to the compressor (Hernandez-Rossette, 2011)(Lin *et al.*, 2018). Evaporation will take place at the compressor outlet, instead of at the compressor inlet stages when the fog water droplets are bigger than the permissive size. If this happens, the amount of power output gained is less because the inter-cooling process efficiency has been dropped (Hernandez-Rossette, 2011). Compressor blade erosion and corrosion will take place if there is an existence of large elements of water droplets (Hernandez-Rossette, 2011). Supplementary technological short comings such as the proper adjustment and adjustment of gas turbine air-cooling, combustion, control and protection systems occur after fogging installation (Hernandez-Rossette, 2011). Safety measure, pre-caution and alertness must be in place to safeguard the compressor stability and blade mechanical integrity.

Lumut Power Plant (LPP) is a Combined Cycle Power plant situated at Segari, Mukim Pengkalan Baru, daerah Manjung, Perak Darul Ridzuan. The plant has been in operation for more than twenty years, with a total dependable capacity of 1943 MW. Lumut Power Plant (LPP) remains the largest combined cycle power plant in Malaysia. The plant is run through by the Malakoff Corporation Berhad subsidiary of Segari Energy Ventures Sdn Bhd (SEV) for Block 1 and 2 while GB 3 Sdn Bhd (GB3) for Block 3 as shown in Figure 1.1 and Figure 1.2. Overall, Lumut Power Plant has a fleet of 9 ALSTOM GT13E2 gas turbines. Fogging system has been installed at GT11 in

March 2011 to boost the gas turbine net active power output by lessening the consumption of compressor loading. Inlet Fogging cooling system is considered due to the fast and simple installation plus the comparatively small capital expenditure among all the inlet cooling methods available in the market (Meher-homji, 2002). However, the installation of fogging system has introduced blade erosion problem to the gas turbine after a few months of operation.

Despite the fact that Chaker et al. (2019) found operational parameters like mass flow rate of water, measurement location, differential pressure applied, and air velocity are important to determine the droplet diameter and spray angle correlations in the experiment. However, in the study by Kumar et al. (2019), the geometrical effect of the impaction-pin nozzle has not been included. Thus, this research is needed to study the geometrical effect of the impaction pin nozzle towards the spray angle and droplets size of the fogging system that is installed in GT11. This is to prevent compressor blade failure like mentioned in the paper of Zdzislaw Mazur et al. (2011). Apart from that, parameters like temperature spread uniformity, fogging droplets size and spray angles are also important and affecting the performance of fogging system (Bhargava *et al.*, 2016). The methodology applied for this research is experimental and numerical using Computational Fluid Dynamic software (Ansys Fluent 14.5).

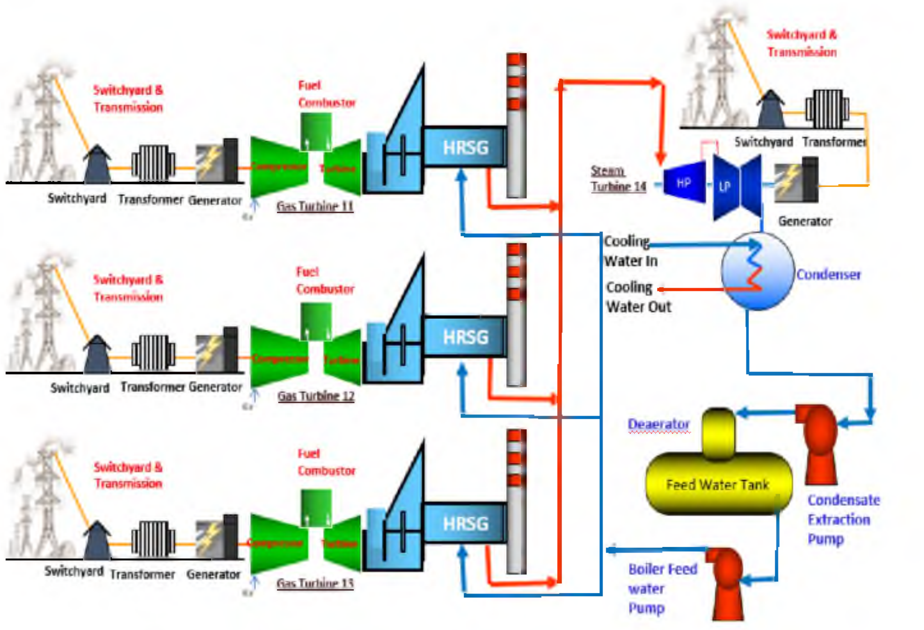

Figure 1.1 LPP Process Overview for One Single Block (Chaker et al., 2019)

Figure 1.2 GT11 at GT Hall

1.2 Problem Statement

GT Inlet cooling system is a well-known option worldwide to boost gas turbines power output during high load demand periods. This is obvious under hot weather when GT power output is dropped (Hernandez-Rossette, 2011). By introducing water-droplet ‘fog’ injection into the turbine air inlet, GT Power output will be increased. Depending on environmental conditions, evaporation of water droplets within the air intake will cool the hot air down and increase air mass flow rate through the turbine (Momin *et al.*, 2016). Turbine power output is boost by ten per cent under this cooling process. As per Alejandro et al. (2011), an important factor like fine water droplets is a must to enable the evaporation all the way to compressor for a good fogging system performance. The risk of compressor blade erosion and corrosion will be increased if there is a presence of large water particles (Hernandez-Rossette, 2011). Compressor stability and blade mechanical integrity cautions must also be taken into consideration to ensure the safety of the operations. Effective water droplets evaporation in the compressor path will be determined by factors like droplet size, water droplet distribution and concentration within the fogging system (Hernandez-Rossette, 2011).

There are two types of Gas Turbine Inlet Fogging system for all classes of combustion gas turbines. The first one which applies just adequate fog to fully evaporate fully the water injection prior to any water droplets collide on rotating turbine parts. The second type is that permits the first several row of compressor blades to run wetted. Typical high-pressure fog nozzles require residence time of approximately three second for a complete evaporation (Bhargava *et al.*, 2019). Water droplets residence time will become shorter when the injection point moves closer to the compressor inlet. About 97% maximum compressor specific work reduction take place in the ISO dry case water injection as high-pressure water will be injected in the air intake ducting at high-ambient temperature conditions (Khan et al., 2012). Water droplets are formed in many ranges of dimensions, as no fog nozzle produces homogeneous droplet size. Big droplets are hard to evaporate in time and will invade on Gas Turbine Air Inlet Guide Vane and compressor blades and eventually will cause erosion and corrosion due to water hammering (Bhargava *et al.*, 2019). Besides that, duct surfaces and silencers will be impinged by a substantial volume spray water as well. An effective drain system and a lined duct are required since the demineralized water is aggressive. A slug of water could be ingested into the compressor causing catastrophic failure if the drain system failed (Bhargava *et al.*, 2019).

The Gas Turbine for this research is located at Lumut Power Plant, Perak. It is named GT11 as per Alstom's KKS coding principal. The rated power output is 145-MW and it is operating at 3000 rpm. GT11 is having 21 compressor stages and 5 gas turbine stages. GT11 has been in service with 150,000 operating hours, which is equivalent to 15 years of operation life. In March 2011, GT11 is installed with a fogging system at the compressor air inlet duct to boost the power output during high load demand on hot days. The outline of the installation is as shown in Figure 1.3 below.

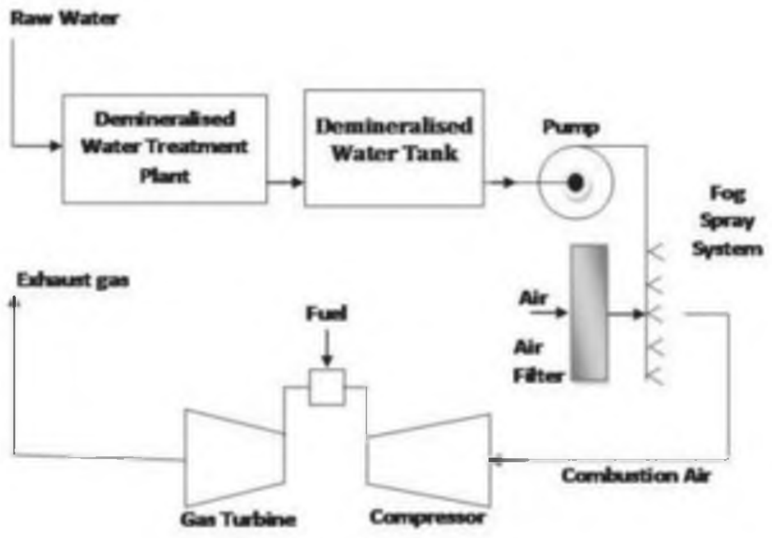

Figure 1.3 Outline of The Gas Turbine 11 Air Inlet Cooling System (Bhargava et al., 2019)

This Capital Expenditure (CAPEX) modification is promising at the beginning stage. However, after four months of operation, Gas Turbine 11 is inspected during the five days duration of minor inspection(borescope). Blade erosion is found at the first to third stage of compressor rotating and stationary blades as shown in Figure 1.6. Eventually, during the 35 days major overhaul in Dec 2012, 1st to 3rd row compressor rotation (VELA), Figure 1.4, and 1st to 2nd row of fixed blades (VELE), Figure 1.5, are replaced as recommended by Original Equipment Manufacturer (OEM) Alstom due to severe base coating erosion resulting from more than 10mm axial base coating erosion.

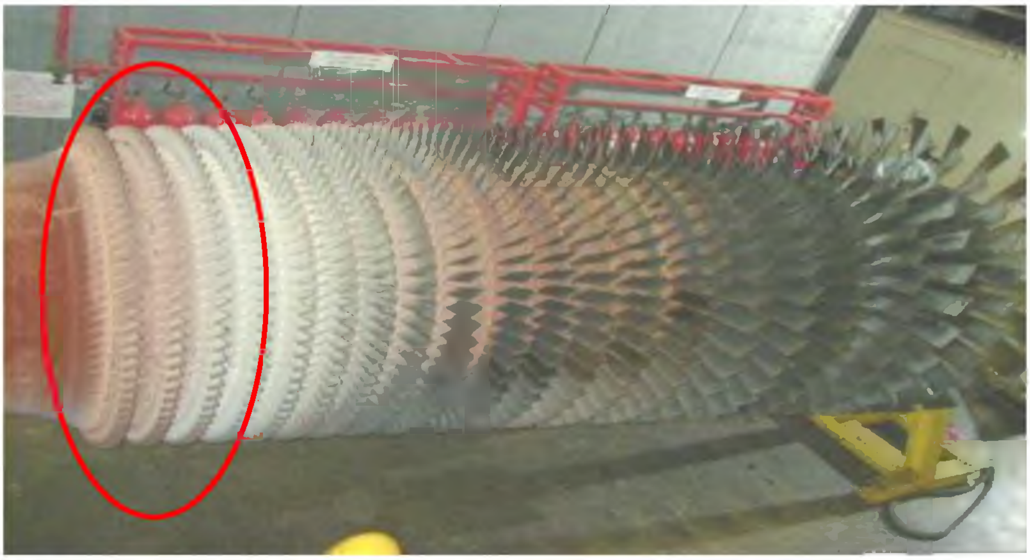

Figure 1.4 GT 1st to 3rd Row of Compressor Moving Blades (VELA)

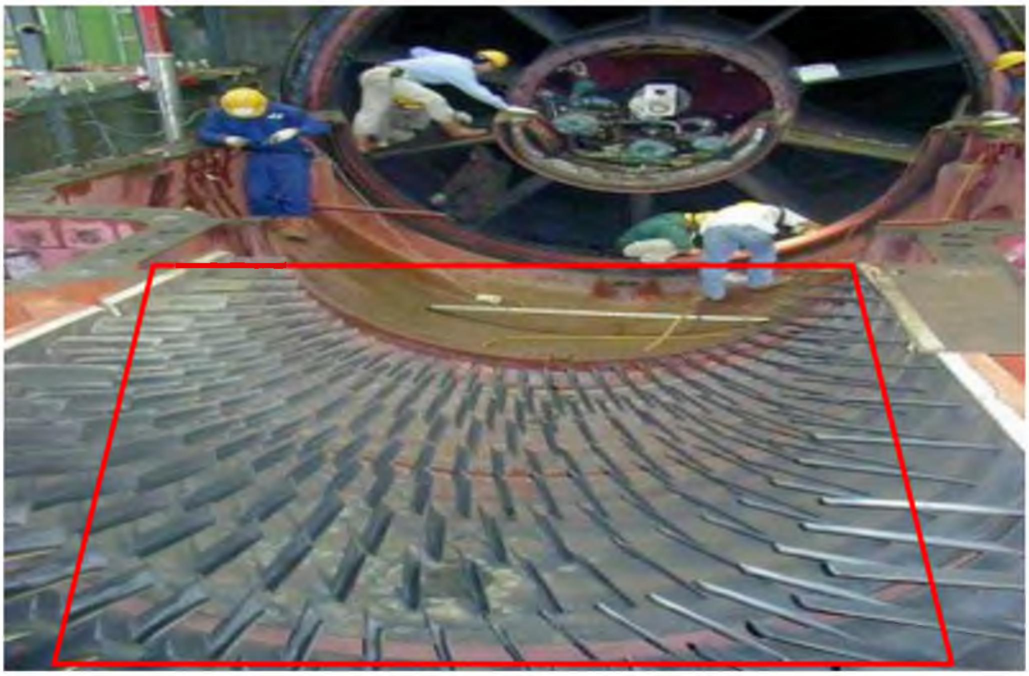

Figure 1.5 GT Compressor Stationary Blades (VELE)

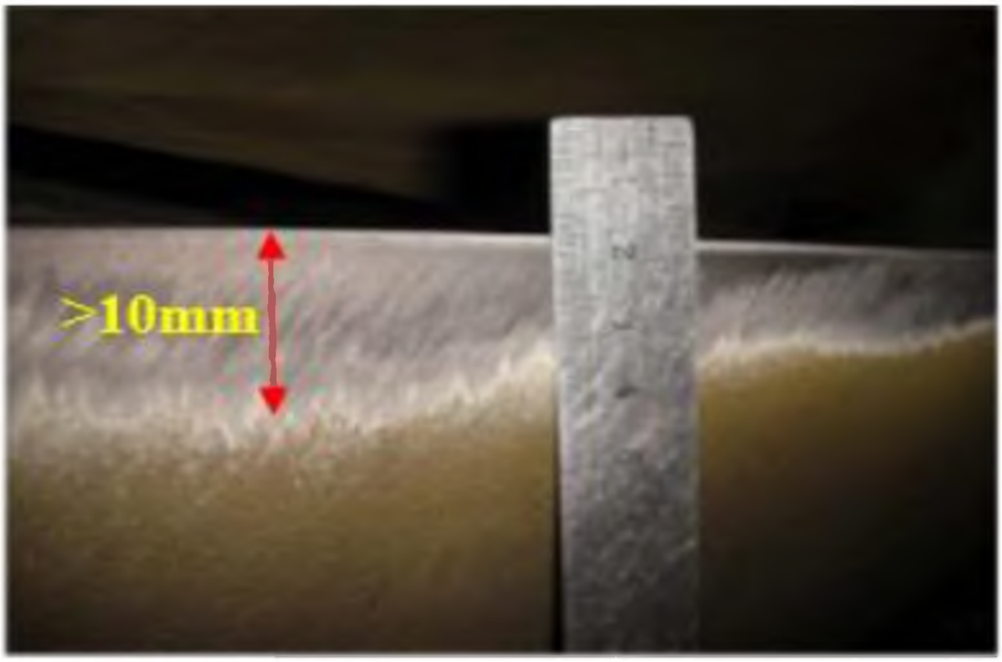

Figure 1.6 GT Compressor Blades Base Coating Erosion

1.3 Objectives

The main objectives of this research are as follows:

- To establish parameters of GT11 Inlet Fogging impaction pin nozzle according to its geometrical effect towards spray angle and droplets size.
- To propose a suitable impaction pin angle range for GT 11 based on spray angle analysis obtained
- To determine suitable number of nozzles for GT11 fogging operation using Number of Nozzle Chart(NONC), Spray Angle Chart(SAC) and Number of Nozzle According Orifice Size Chart(NONAOSC)

1.4 Scope

The scope of this research involved two sections. The first section is experimental analysis on spray angle and droplets size produced by the impaction pin nozzle angle of 30°, 60° and 90° with different orifice size of 0.5mm, 1.0 mm & 1.5mm. The second section of the research is numerical simulation validation using CFD software on the spray angle and droplets size results produced by the impaction pin nozzle angle with different orifice sizes in the experiment. Two dimensional and three dimensional(2D & 3D) Computational Fluid Dynamics (CFD) Ansys Fluent 14. 5 (Hamdani *et al.*, 2015b) are used in the second section of this research. The experimental work is using the experimental apparatus and data acquisition system available in laboratory Uitm, Shah Alam. Droplets size and spray angle performed by the impaction pin nozzle angle and different orifice size are determined as the analysis objective in view of Root Cause Analysis (RCA) has been carried out by the Operation, Maintenance and Engineering team Lumut Power Plant as per Figure 1.7 below. The Fault Tree Analysis modelling methodology is used by the team and verification on other aspects such as low water pressure, low air flow rate, chokage of nozzle filter and water inlet orifice have been done and all are in good order. The only unaccomplished task is in terms of spray angle and droplets size. Hence this research is needed to conclude a solution for this issue. Three impaction pin nozzle angles namely 30°, 60°& 90° and orifice sizes of 0.5mm, 1.0mm & 1.5mm are fabricated in Kolej Kemahiran Tinggi MARA Kuantan, Pahang, using Direct Metal Laser Sintering (DMLS) three-dimension printing processes. The research objective is to establish parameters of GT11 Inlet Fogging impaction pin nozzle according to its geometrical effect towards spray angle and droplets size. Hence, to propose a suitable impaction pin angle range for GT11 based on spray angle analysis obtained from the research. Last but not least, the final objective of this research is to analyze suitable number of nozzles for GT11 fogging operation by referring to Number of Nozzle Chart (NONC), Spray Angle Chart (SAC) and Number of Nozzle According Orifice Size Chart (NONAOSC). Due to laboratory testing equipment constraint, the experiment is unable to proceed for the smallest orifice size of 0.5mm, and the number of different pin angle is not varied. The changes made to the experimental setup are based on water pressure, water flow, impaction pin angle and orifice size. All experimental work is conducted and completed by using the test-rig at laboratory Uitm, Shah Alam.

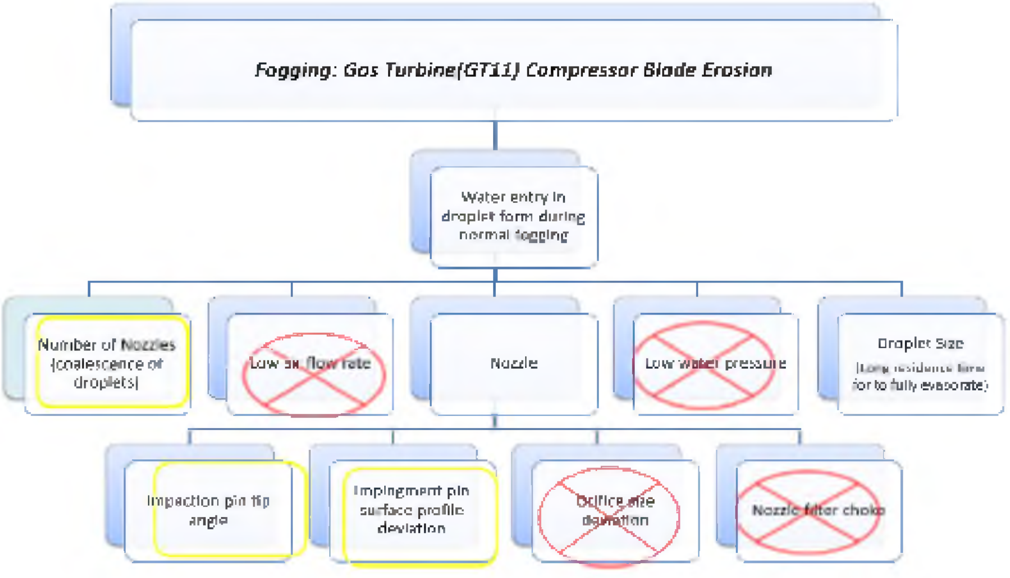

Figure 1.7 RCA GT11 Compressor Blade Erosion (Hernandez-Rossette, 2011)

In view of the unavailability of high-pressure (138bar) Gas Turbine Fogging testing equipment and for simplicity of the research work, a low-pressure testing experiment set-up which is available at laboratory Uitm, Shah Alam is used as the testing mechanism for this research, ie: 0.38bar to 0.68bar. Besides that, there is another limitation in the experimental section of this research, which is the inability to proceed with the testing of the smallest orifice size of 0.5mm as no flow is detected in the experiment. Another limitation in the numerical simulation section of the research is the assumption of ambient air (hot air) which ignores the presence of moisture in the air.

1.5 Significance of the Research

Overall, the nozzle geometry and other specific features such as operating pressure, water flow rate and density to the application will vary the spray angles and droplets size. The analytical method and the nozzle testing set proposed in this research can be used as a reference to gain optimum solution for nozzle application in a Gas Turbine inlet cooling system and to get a complete evaporation process of water droplets. Generally, Gas Turbine blade erosion caused by fogging operation can be eliminated by establishing parameter of inlet fogging impaction pin nozzle according to its geometrical effect towards spray angle and droplets size. The proposal of suitable impaction pin angles range for Gas Turbine 11 can reduce the number of fogging nozzles of Gas Turbine 11 and thus can prevent coalesces of water droplets. Finally, the proposed reference charts of NONC, SAC and NONAOSC can enable gas turbine fogging installation and operation to become easier and practical in the power plant industry especially to those midlife power plant.

In the past five years, approximately 1300 gas turbines in the world are already utilising inlet fogging systems because this method becomes very common and well-known (Zhang, Zheng, *et al.*, 2016). The number has been increased from 700 to 1300 gas turbines since 2007 according to Rishack (2007) and the trend is increasing linearly as per showing in the graph in Figure 1.8 below. Hence the outcome of this research is important for the Gas Turbine Fleet in the world.

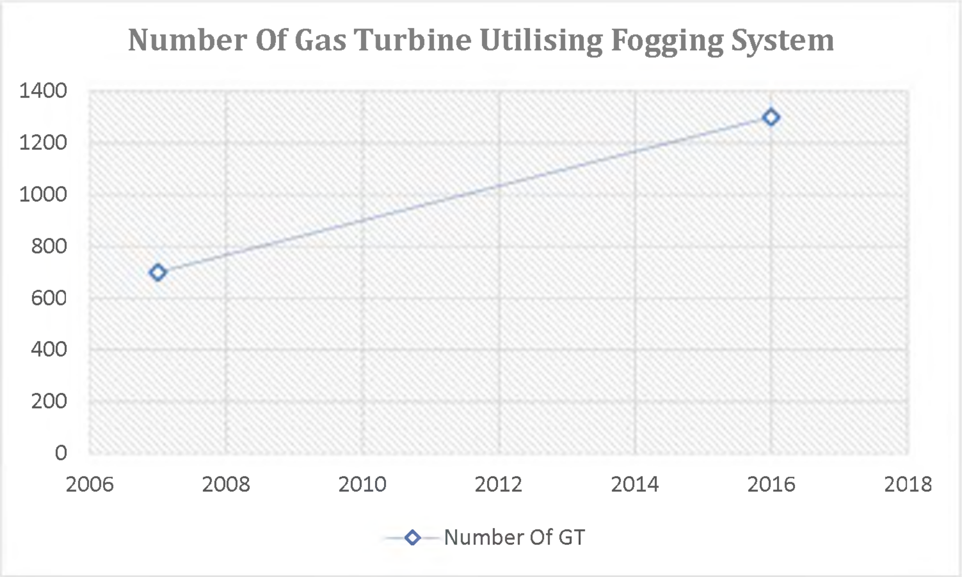

Figure 1.8 Number of Gas Turbine Utilising Fogging System

This research is needed in evaluating the most effective fogging nozzles in view of the fact that compressor blades replacement cost is expensive where the total cost is around RM 3.3 million according to Foreign Currency Exchange rate to date as shown in the Table 1.1 below. Ultimately, to eliminate the compressor blade erosion problem which can minimize the risk of compressor damage due to this power enhancement. The power enhancement plan will be resumed and continued with all remaining 8 units of Gas Turbine in Lumut Power Plant once this research has been accomplished. In total, there are 9 Gas Turbine in Lumut Power Plant. Hence, this research is important in avoiding the compressor blades erosion which can lead to blades replacement for all the Gas Turbines. The cost avoidance or saving is huge, which resulting in RM3.3 million multiply by 9 Gas Turbines and equals to RM29.7 million (Close to RM30 million). The saving is huge in maximizing the company's revenue. Consequently, the impact of this research to the company's profit and loss statement is big if the blades erosion matter which is caused by fogging operation persist.

Table 1.1 Cost Analysis for Replacement of GT 1st to 3rd Row Compressor Blades

	Unit Price	**Unit Price**	**Quantity**	**Total Price**
New Blade	**Swiss Franc, CHF**	**RM**		**RM**
Compressor Rotating Blades 1st Row (VELA 1)	9,758	43,911	25	1,097,775
Compressor Rotating Blades 2nd Row (VELA 2)	4,976	22,392	31	694,152
Compressor Rotating Blades 3rd Row(VELA 3)	4,890	22,005	31	682,155
Compressor Station Blades 1st Row(VELE 1)	3,595	16,178	26	420,615
Compressor Station Blades 2nd Row (VELE 2)	3,150	14,175	32	453,600
			Total Cost	***RM3,348,297***

*Foreign Exchange Rate, 1 Swiss Franc (CHF) = RM4.51

1.6 Summary

Whenever ambient air temperature is increased, the GT power output will be decreased significantly (Domachowski and Dzida, 2015). This is because of the reduction of mass flow for intake air when the air density is reduced. Combined cycle power plants Gas Turbines started to use inlet fogging as a power extension method to boost the power output (Ehyaei et al., 2015). In the past 5 years, approximately 1300 gas turbines in the world are already utilizing inlet fogging systems because this method becomes very common and well-known (Zhang, Zheng, et al., 2016). Fogging system has been installed at GT11 in March 2011 to boost the gas turbine net active power output. However, the installation of fogging system is promising at the beginning and it has introduced a blade erosion problem to the gas turbine after four months of operation. Erosion is found at the first to third stages of compressor rotating and stationary blades. The compressor blades replacement cost is expensive where the total cost is around RM 3.3 million according to Foreign Currency Exchange rate. Ultimately, this research is needed in evaluating the most effective fogging nozzles to eliminate the compressor blade erosion problem which can minimize the risk of compressor damage due to this power enhancement. The power enhancement plan will be resumed and continued for all the remaining eight units of Gas Turbine in Lumut Power Plant once this research has been accomplished by achieving the research objective as mentioned above. Even though Chaker et al. (2019) found that operational parameters like mass flow rate of water, measurement location, differential pressure applied, and air velocity are important to determine the droplet size and spray angle correlations in his research. However, in the study by Kumar et al. (2019), the geometrical effect of the impaction-pin nozzle has not been included. Thus, this research is needed to study the geometrical effect of the impaction pin nozzle towards the spray angle and droplets size of the fogging system that is installed in GT11. This is to prevent a compressor blade failure like mentioned in the paper Zdzislaw Mazur et al. (2011).

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LIST OF PUBLICATIONS

Journal publication

1. **Tan Beng Chiat**, Kahar Osman, Kamariah Md Isa, Ahmad Hussein Abdul Hamid and Zulkifli Abdul Ghaffar (2020) “Impaction Pin Angle and Nozzle Orifice Dimension Design Effects In Spray Patterns For Gas Turbine Inlet Cooling” Vol 8, pp 26-32. Publisher, *Journal of Built Environment, Technology and Engineering.*

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